GRASPER: A Multisensory Based Manipulation System for Underwater Operations

P. J. Sanz, A. Peñalver, J. Sales, D. Fornas, J. J. Fernández, J. Pérez, J. Bernabé
Computer Science and Engineering Department
University of Jaume-I (UJI)
12071 Castelló de la Plana, Spain

***Abstract*—This paper presents the progress that has been made recently in the TRITON project. The TRITON project is an on going research project being carried out in Spain which has as principal objective the production of an AUV capable of autonomous underwater interventions. The GRASPER sub-project focuses on developing the necessary manipulation skills. Currently, a lot of research in the underwater robotics context is developing increasing levels of autonomy for all kinds of intervention operations, which always require some kind of physical interaction. However, if autonomous robotic manipulation on land remains a relatively undeveloped field, the situations is at an even more primitive stage in underwater scenarios where currently the systems are tele-operated by an expert user from a surface vessel. Only very few underwater systems have the capacity to carry out manipulation without any kind of umbilical cables teleoperating these actions. In particular, this work introduces a new approach for increasing the autonomy levels of an underwater manipulation system, discussing also preliminary results. In order to test this concept, different objects, without predefined models, are approached and recovered from the bottom in water tank conditions. To achieve this purpose, a scan of the scene is performed using a structured laser beam attached to the forearm of the manipulator. At the same time, a digital video camera is used to capture the scene with the laser beam projected onto the object. The laser stripes are triangulated to obtain a 3D point cloud. Moreover, the underwater robot gripper is provided with strain gauge tactile sensors, which enable the execution of a more reliable grasp. On the other hand, the process is shown inside an underwater simulator previously developed, named UWSim, acting in this case as a virtual representation of the real environment. This virtual representation allows the user to specify the grasp, highlighting how the virtual grasp will be defined for the selected target. The feasibility and reliability of the underwater manipulation system is demonstrated though the experimental results.**

***Index Terms*—Underwater intervention mission, 3D reconstruction, semiautonomous grasping, underwater object recovery.**

I. Introduction

GRASPER (under the responsibility of University of Jaume-I UJI, and addressing the problem of the "Autonomous Manipulation") represents only a sub-project inside a Spanish Coordinated Project, entitled: TRITON, "Multisensory Based Underwater Intervention through Cooperative Marine Robots", which includes two other sub-projects: COMAROB ("Cooperative Robotics", under the responsibility of University of Girona, UdG), and VISUAL2 ("Multisensorial Perception", under the responsibility of University of Balearic Islands, UIB). In summary, TRITON is a marine robotics research project focused on the development of intervention technologies really close to the real needs of the final user and, as such, it can facilitate the potential technological transfer of its results. The project proposes two scenarios to test the concept, and to demonstrate the developed capabilities: (1) the search and recovery of an object of interest (e.g. a "black-box mockup" from a crashed airplane), and (2) the intervention of an underwater panel in a permanent observatory.

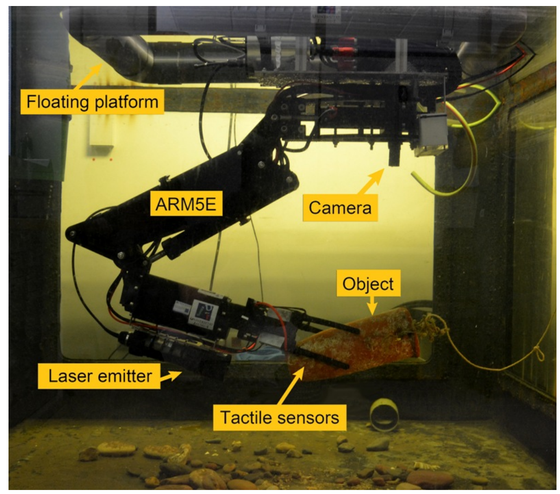

Fig. 1. The considered scenario with the mechatronic systems and the water tank at IRS-Lab (Interactive and Robotic Systems Lab, UJI, Spain).

The specific objectives for the GRASPER sub-project are the following:

- O1: To develop the user interface and simulation capabilities needed for TRITON.
- O2: To generate all the mechatronics and sensor improvements to succeed in the autonomous manipulation requirements.
- O3: To develop new planning and control strategies for manipulation, making use of range and visual information, finally leading to free floating manipulation.

In this paper, recent progress towards autonomous underwater manipulation, by using UWSim as 3D simulation tool (concerning O1), sensory improvements based on laser, vision and tactile sensors devices (concerning O2), and new algorithms

978-1-4799-0652-9/13 $31.00 © 2013 IEEE
DOI 10.1109/SMC.2013.689

for grasping approach and execution (concerning O3) will be demonstrated and discussed.

II. State of The Art

In the area of underwater intervention, ALIVE [1] (FP5 EU project, AUV with manipulation capabilities), and SAUVIM [2] (University of Hawaii, Semi-Autonomous Underwater Vehicle for Intervention Missions) have become milestone projects. The result of both projects have lead to significant reductions in cost thanks to its autonomous operation, which avoids the need for extremely expensive intervention ships.

Planning a grasp is generally known to be a difficult problem due to the large search space resulting from all possible hand configurations, grasp types and object properties that occur in regular environments. The dominant approach to this problem has been the model-based paradigm, in which the object shape, contacts, and forces are modelled according to physical laws. So, the research has been focused on grasp analysis (the study of the physical properties of a given grasp) and grasps synthesis (the computation of grasps that meet certain desirable properties) [3]. Unfortunately, these approaches have failed to deliver practical implementations, mainly because they rely on assumptions that are difficult to satisfy in complex and uncertain environments.

The current trend is to incorporate sensor information for grasp planning and synthesis, such as vision [4]–[8] or range sensors [9]. Recently, the knowledge-based approach has been combined with vision-force-tactile feedback and task-related features that improve the robot performance in real scenarios [10], [11].

Regarding autonomous manipulation in underwater environments, so far very limited research has been carried out. Only the very recent TRIDENT project [12] has demonstrated quasi-autonomous manipulation capabilities without any requirement for the objects to be analysed, and a bit earlier, SAUVIM project demonstrated also semi-autonomous grasping skills, although making use of predefined object models with specific markers for easy recognition. In the author's previous project RAUVI [13], a novel user interface with integrated autonomous grasp planning capabilities was developed [14], and real grasping and hooking experiments were also successfully carried out.

In summary, there remains a huge amount of research to be done in the grasping and manipulation field , and this is even more true for underwater scenarios. In the shallow water context, new complexities arise, increasing the difficulty of controlling grasping and manipulation actions with agility capabilities. Under these very hostile conditions, only a few robot systems are endowed with semi-autonomous manipulation capabilities, mainly focused on specialized operations requiring a reasonably structured environment, like those devoted to the offshore industries.

This paper is organized as follows: in Section III the experimental arrangement is described. Then, Section IV details the strategy for grasping. Results and conclusions are detailed in Sections V and VI respectively. Finally, in section VII, the current work in progress is described.

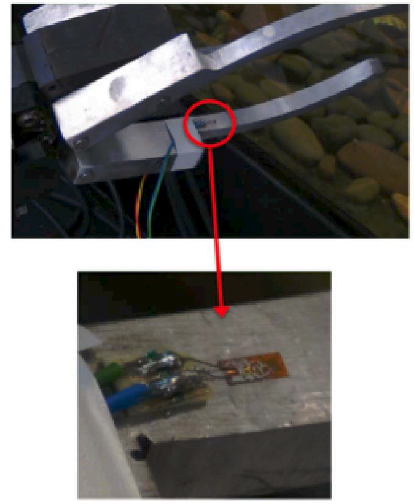

Fig. 2. Detail of the tactile sensor based on strain gauges installed on the jaw gripper. The gripper is mounted on the ARM5E robotic arm.

III. Experimental Arrangement

In a first attempt to deal with the problem of the docked manipulation considered in the TRITON project, the following scenario has been used. The scenario includes a 2m x 2m x 1.5m water tank, whose floor recreates a real seafloor (see Figs. 1 and 4). The underwater vehicle consists of a fixed 4 D.O.F. robotic arm (CSIP Light-weight ARM5E [15] with a sensorized gripper containing tactile sensors based on strain gauges in its end-effector, see Fig. 2) that is attached to an underwater vehicle floating inside the tank (see Fig. 1). The vehicle is equipped with an underwater camera (Bowtech 550C-AL) that is placed near the base of the arm and is looking downwards. The 3D reconstruction is done with a laser stripe emitter (Tritech SeaStrip) attached on the forearm of the manipulator. The user interface is provided by the Underwater Simulator UWSim [16].

IV. Exploring Grasping Strategies Through GRASPER

After success with previous manipulation strategies, tested in different scenarios but using mainly a hooking device or a very simple parallel jaw gripper (see Fig. 3), this paper explores a new approach, discussing also some preliminary results. Prior tests included the grasping of a black-box mockup in a controlled environment: the water tank at the IRS-Lab facilities at UJI (see Fig. 3 left). Later, a more sophisticated experiment was performed, for finding and recovering the same black-box mockup at the CIRS pool (Research Center In Undewater Robotics, UdG, Spain) [17], with the mechatronic configuration that can be seen in Fig. 3 (right).

Currently, and bearing in mind that one of the final validation scenarios of TRITON requires that the intervention

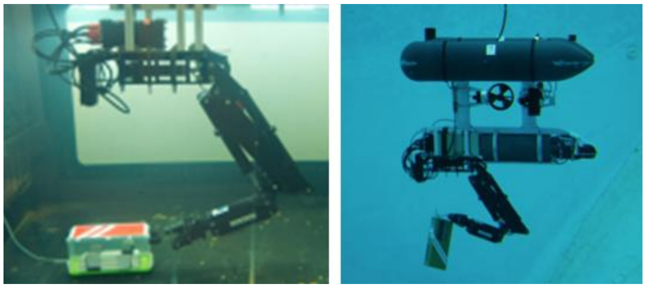

Fig. 3. Fixed based manipulation of a black-box with a parallel jaw gripper (IRS-Lab, UJI, Spain) (left). Black-box mockup search and recovery in a pool (CIRS, UdG, Spain) (right).

autonomous underwater vehicle (I-AUV) makes a docking to a panel structure before starting manipulation, we came back to previous experiments where only those D.O.F. concerning the hand-arm system were available. Thus, a combination of structured light and a virtual simulation environment that allows a user to specify the grasping points of a real unknown object in a 3D reconstructed scenario is presented. This approach allows semi-autonomous grasping of underwater unknown objects by using a robotic arm mounted in a fixed underwater platform. It is worth noting that this work represents a different approach to those previously presented by authors [18] where a mobile base hand-arm system was used, without any tactile sensory information available and omitting the grasping determination problem. All these new aspects are now included in the present work, where the previously developed simulation tool, named UWSim [16] has been used to allow the user to visualize the 3D representation of the scene and the best grasp determination, based on the previous grasp specification.

A. 3D Reconstruction of the Scene

In order to reconstruct the geometry of the unknown object by using the laser strip, the floor is scanned by moving the elbow joint of the manipulator at a constant velocity (see Fig. 4). During the scan, a visual processing algorithm runs in parallel: the laser peak detector, which is in charge of segmenting the laser stripe from the rest of the image and computing the 3D points [18]. With these points, a 3D point cloud of the scene is built and represented on the simulator (see Fig. 6).

B. Grasp Specification

Once the scene has been reconstructed, the virtual environment, the 3D point cloud, and a snapshot of the scene taken by the camera is displayed on the screen.

The user then specifies the grasp by selecting two antipodal grasp points on the snapshot image (Fig. 5). The projection of those 2D points specified by the user define two 3D lines that are used to define a 3D volume (with a fixed width). This volume is intersected with the point cloud, and thus, only those points lying inside are kept. The next step is to remove outliers and to build a downsampled cloud. All these operations

Fig. 4. The 3D laser stripe emitter attached to the arm while scanning the floor (top). Laser peak detection (highlighted in red colour) superposed to the camera image (bottom).

significantly reduce the size of the point cloud, making it possible to perform all posterior computations faster.

The best grasp determination is then calculated by the system, and it is shown onto the 3D representation. It consists of a CAD model of the end-effector of the manipulator, thus improving the virtual representation of the real grasp (Fig. 7).

C. Supervised and Real Execution

Unlike the system used in the previous work, whose manipulator consisted in a robotic arm attached to a vehicle

Fig. 5. Snapshot of the scene captured by the camera where the user selects the two antipodal grasp points.

completing a system with more than 6 D.O.F., in this study, the possibility that the system could have less than 6 D.O.F. is considered (in our case, the aforementioned robotic arm has only 4 D.O.F).

This constraint causes that not all the points selected by the user generate a grasp specification that is reachable by the robot arm, that is, the resultant 3D point can not be reached in a proper orientation or falls outside the workspace of the manipulator.

For this reason, a supervised grasp strategy is adopted. In this strategy, the system searches the closest feasible grasp to the position selected by the user through the points (refer to Algorithm 1). Once the best feasible grasp has been found, the resulting position and orientation of the end-efector, is displayed on the simulation evironment (Fig. 7). At this moment the user can see how the grasp will be performed and he is able to decide whether to launch the autonomous grasp execution or to select two different grasp points. In this latter case, the search for the best grasp is executed again.

Algorithm 1 Best feasible grasp determination

Require: $p1, p2$
  $point1 \leftarrow (p1_x, p1_y)$
  $point2 \leftarrow (p2_x, p2_y)$
  $highest\_3Dpoint \leftarrow (f_x, f_y, f_z)$
  $lowest\_3Dpoint \leftarrow (c_x, c_y, c_z)$
  $best\_pos \leftarrow ((p1_x + p2_x)/2, (p1_y + p2_y)/2, (f_z + c_z)/2)$
  for $roll \leftarrow -\pi : 0.1 : \pi$ **do**
    for $pitch \leftarrow -\pi : 0.1 : \pi$ **do**
      for $yaw \leftarrow -\pi : 0.1 : \pi$ **do**
        $current\_frame \leftarrow [best\_pos, [roll, pitch, yaw]]$
        $grasp\_frames \leftarrow grasp\_frames + inv\_kin(current\_frame)$
      end for
    end for
  end for
  for $eachframeingrasp\_frames$ **do**
    if $distance(frame.position, best\_position) < closest\_frame$ **then**
      $closest\_frame \leftarrow frame$
    end if
  end for

To determine the best grasp position and orientation, the following steps are taked (refer to Algorithm 1 and Fig. 6 to follow the explanation):

- The best position (*best_pos*) to perform the grasp is defined as the middle point between the two points selected by the user (*point1* and *point2*). In the reduced point cloud, the highest (*highest_3Dpoint*) and the lowest (*lowest_3Dpoint*) points are looked for, and the height of the best position is defined as the height between the two.
- In the next step, an iterative algorithm (*inv_kin)* is used to solve the inverse kinematic of the manipulator to reach the best position with every orientation that we are interested in. This algorithm returns if the arm is able to reach this position and orientation and if it is not able, also returns the closest position of the arm which is able to reach with the given orientation.
- Once every orientation has been solved, the distance between each result of the inverse kinematic algorithm and the best position is determined.
- Finally, the closest result to the best position (*closest_frame*) is selected, and the CAD model of the end-effector is displayed on the simulator in the position and orientation selected by the algorithm. Contrarily, if the distance is bigger than a threshold, an error message is shown to the user.

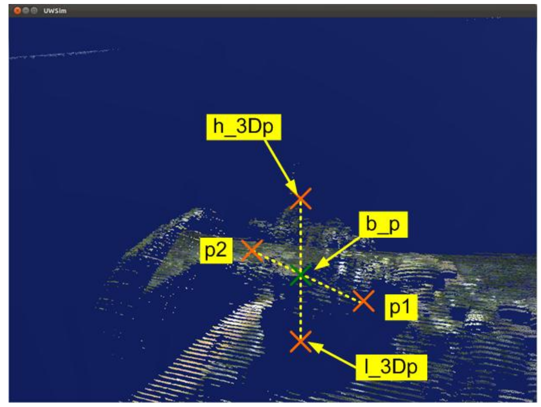

Fig. 6. Reconstructed scene in the UWSim underwater simulator, represented by 3D point cloud data. Relevant points used by the best grasp determination algorithm are also represented: *p1 (point1)*, *p2 (point2)*, *b_p (best_pos)*, *h_3Dp (highest_3Dpoint)* and *l_3Dp (lowest_3Dpoint)*.

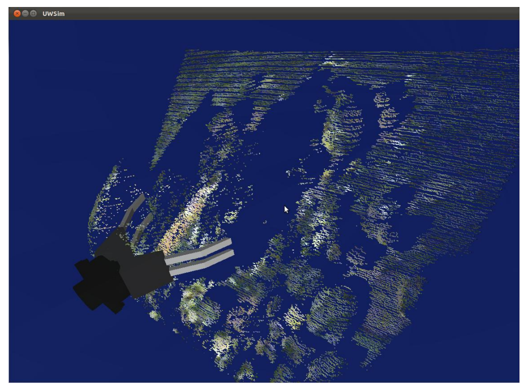

Fig. 7. Best determined grasp. The virtual 3D representation of the robot end-effector is displayed over the 3D point cloud data.

D. Grasping and Tactile Reactive Behaviour

In the case that the user decides to launch the grasp execution, the end-effector autonomously tries to reach the position and orientation selected in the previous step (Fig. 8).

In order to cope with the possibility of a seafloor impact by the gripper, a reactive behaviour based on tactile information has been developed. When this happens, it is normally due to CAD modeling errors of the mechatronic system (arm

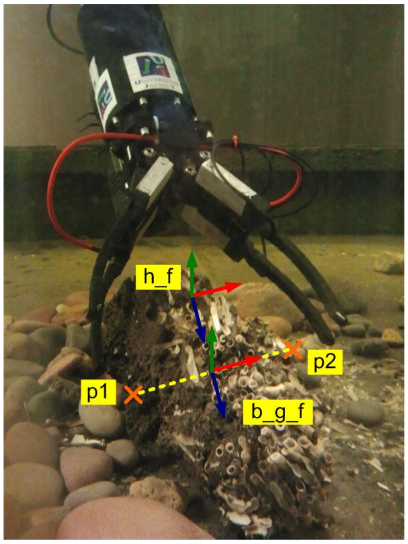

Fig. 8. Grasping determination parameters represented over the real scenario: *p1 (point1)*, *p2 (point2)*, *h_f (hand_frame)* and *b_g_f (best_grasp_frame)*.

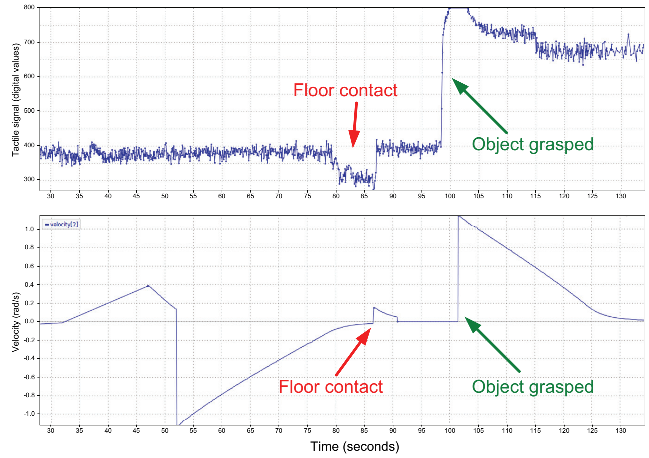

Fig. 9. Time evolution (in seconds) of the analog signal from tactile sensors (top) and elbow control joint velocity (bottom).

dimensions, camera and laser position) that can affect the 3D reconstruction process and the kinematic control. Whith a reactive behaviour, in case that the end-effector touches anything while it is reaching the correct position, the tactile sensors would notice this contact and the arm would be stopped. Then, the elbow joint would move up the arm until the tactile sensors will not detect any contact.

When the end-effector reaches the final position, it is because either it has properly reached the previously defined position and orientation, or because the end-effector has touched the seafloor and thus the final position has been properly modified. At this moment, the grasp begins, and the sensorized gripper starts closing until the object is contacted. Again, the system obtains feedback when the object is grasped. Then, the arm with the recovered object moves back to the home position.

The output singal from the tactile sensors and the elbow control joint velocity in response to the signals is represented in Fig. 9. It is noticeable that the presure that the sensors need to detect in order to warn the system when the object has been grasped is considerably higher than the presure needed to detect a contact with the floor. The reason is that the objects need to be strongly grasped in order to be raised.

V. Experimental Results

The proposed approach has been thoroughly tested with two different objects: a wooden trunk and an amphora (Fig. 10). The first one produces good 3D reconstructions and good grasps despite its non-uniform shape. In the second case, the shape is more uniform but due to some white spots on it, which reflect the laser light, the reconstructions are not so good and therefore, the grasp is not always satisfactory. Despite this issue, the overall success ratio is around 80%, thanks to the adopted supervised grasp strategy. The described experiments have been executed in a personal computer (Intel Core i5 650 @ 3.2GHz, 4Gb RAM) running Ubuntu/Linux 11.10, with the following times: 3D point cloud reconstruction (16.878s, comprising the laser scan of the surface), laser peak detection (36.375ms per frame) and best feasible grasp determination algoritm (<1ms, depending on the number of iterations).

The system in action including the 3D scene reconstruction, the grasp specification, determination and execution can be seen on-line in two different videos: (1) grasping the wooden trunk (http://youtu.be/VOLNBWfeoLs) and (2) grasping the amphora (http://youtu.be/c62FTTycxsQ).

Moreover, an experiment to test the tactile sensors when the arm collides with the floor has been done (http://youtu.be/42ZklVwNaqcx). The feedback from the tactile sensors (Fig. 9), minimizes the efect of collisions and improves the manipulation thus assuring that the object is properly grasped.

VI. Conclusion

In this paper, recent progress towards autonomous underwater manipulation has been presented. The proposed approach allows the semi-autonomous grasping of underwater unknown objects by using a robotic arm mounted in a fixed underwater platform. It is based on a combination of structured light and a virtual simulation environment that allows a user to specify the grasping points of a real unknown object in a 3D reconstructed scenario. This approach provides a good alternative to the use of other sensors that are not able to perform well in underwater environments (low visibility, bad propagation of signals, humidity, etc.). The use of a simulation environment provides 3D visual feedback and a preview of the specified grasps.

VII. Work in Progress

Alternatively, as work in progress, a different approach to grasp specification is being explored. It consists of using the reconstructed point cloud in order to approximate the shape of the objet to a primitive shape with point cloud processing

Fig. 10. Experimental validation. Grasping an amphora (top). Grasping a wooden trunk (bottom).

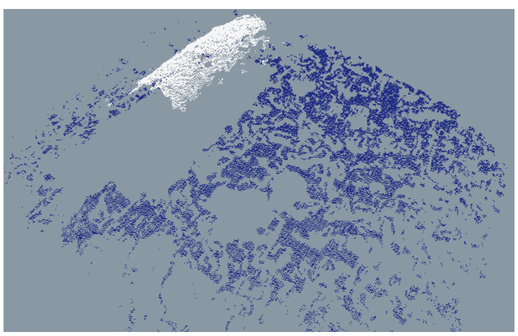

Fig. 11. Point cloud segmentation of the scene for grasp specification.

and RANSAC algorithms (Fig. 11). With this approach, the user is not required to input the pair of grasping points, but he still validates the autonomously obtained grasp posture. These experiments are currently limited to objets with a given shape (in this case an amphora with cylindrical shape) and the method has some parameters that must be tuned. The result is a semi-autonomous system that works in a constrained scenario, but it continues advancing towards the full autonomy.

ACKNOWLEDGMENT

This research was partly supported by Spanish Ministry of Research and Innovation DPI2011-27977-C03 (TRITON Project), by the European Commission's Seventh Framework Programme FP7/2007-2013 under Grant agreement 248497 (TRIDENT Project) and by Foundation Caixa Castelló-Bancaixa PI.1B2011-17.

REFERENCES

[1] J. Evans, P. Redmond, C. Plakas, K. Hamilton, and D. Lane, "Autonomous docking for Intervention-AUVs using sonar and video-based real-time 3D pose estimation," in *OCEANS 2003. Proceedings*, vol. 4, 2003, pp. 2201–2210 Vol.4.

[2] G. Marani, S. K. Choi, and J. Yuh, "Underwater autonomous manipulation for intervention missions AUVs," *Ocean Engineering*, vol. 36, no. 1, pp. 15 – 23, 2009, autonomous Underwater Vehicles. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S002980180800173X

[3] K. B. Shimoga, "Robot grasp synthesis algorithms: a survey," *Int. J. Rob. Res.*, vol. 15, no. 3, pp. 230–266, Jun. 1996. [Online]. Available: http://dx.doi.org/10.1177/027836499601500302

[4] A. Morales, G. Recatala, P. Sanz, and A. Del Pobil, "Heuristic vision-based computation of planar antipodal grasps on unknown objects," in *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, vol. 1, 2001, pp. 583–588 vol.1.

[5] A. Hauck, J. Ruttinger, M. Sorg, and G. Farber, "Visual determination of 3D grasping points on unknown objects with a binocular camera system," in *Intelligent Robots and Systems, 1999. IROS '99. Proceedings. 1999 IEEE/RSJ International Conference on*, vol. 1, 1999, pp. 272–278 vol.1.

[6] J. Coelho, J. Piater, and R. Grupen, "Developing haptic and visual perceptual categories for reaching and grasping with a humanoid robot," *Robotics and Autonomous Systems*, vol. 37, no. 2–3, pp. 195 – 218, 2001, humanoid Robots. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0921889001001580

[7] R. Cipolla and N. Hollinghurst, "Visually guided grasping in unstructured environments," *Robotics and Autonomous Systems*, vol. 19, no. 3–4, pp. 337 – 346, 1997, intelligent Robotic Systems SIRS'95. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0921889096000607

[8] P. Sanz, A. Requena, J. Inesta, and A. Del Pobil, "Grasping the not-so-obvious: vision-based object handling for industrial applications," *Robotics Automation Magazine, IEEE*, vol. 12, no. 3, pp. 44–52, 2005.

[9] R. Rusu, A. Holzbach, R. Diankov, G. Bradski, and M. Beetz, "Perception for mobile manipulation and grasping using active stereo," in *Humanoid Robots, 2009. Humanoids 2009. 9th IEEE-RAS International Conference on*, 2009, pp. 632–638.

[10] M. Prats, P. J. Sanz, and A. P. Pobil, "A framework for compliant physical interaction," *Autonomous Robots*, vol. 28, no. 1, pp. 89–111, 2010. [Online]. Available: http://dx.doi.org/10.1007/s10514-009-9145-8

[11] ——, "Reliable non-prehensile door opening through the combination of vision, tactile and force feedback," *Autonomous Robots*, vol. 29, no. 2, pp. 201–218, 2010. [Online]. Available: http://dx.doi.org/10.1007/s10514-010-9192-1

[12] P. J. Sanz, R. Marin, J. Sales, G. Oliver, and P. Ridao, *Recent advances in underwater robotics for intervention missions. Soller harbor experiments*. Spain: Low Cost Books, 2012.

[13] P. Sanz, M. Prats, P. Ridao, D. Ribas, G. Oliver, and A. Ortiz, "Recent progress in the RAUVI project: A Reconfigurable autonomous underwater vehicle for intervention," in *ELMAR, 2010 PROCEEDINGS*, 2010, pp. 471–474.

[14] J. Garcia, J. Fernandez, P. Sanz, and R. Marin, "Increasing autonomy within underwater intervention scenarios: The user interface approach," in *Systems Conference, 2010 4th Annual IEEE*, 2010, pp. 71–75.

[15] J. J. Fernández, M. Prats, J. C. García, R. Marín, and A. Peñalver, "Manipulation in the seabed: A new underwater robot arm for shallow water intervention," in *Embedded Systems, Computational Intelligence and Telematics in Control*, Würzburg, Germany, 04 2012.

[16] M. Prats, J. Perez, J. Fernandez, and P. Sanz, "An open source tool for simulation and supervision of underwater intervention missions," in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, 2012, pp. 2577–2582.

[17] M. Prats, D. Ribas, N. Palomeras, J. C. García, V. Nannen, S. Wirth, J. J. Fernández, J. P. Beltrán, R. Campos, P. Ridao, P. J. Sanz, G. Oliver, M. Carreras, N. Gracias, R. Marín, and A. Ortiz, "Reconfigurable AUV for intervention missions: a case study on underwater object recovery," *Intelligent Service Robotics*, vol. 5, no. 1, pp. 19–31, 2012. [Online]. Available: http://dx.doi.org/10.1007/s11370-011-0101-z

[18] M. Prats, J. Fernandez, and P. Sanz, "Combining template tracking and laser peak detection for 3D reconstruction and grasping in underwater environments," in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, 2012, pp. 106–112.